DYNAMIC SOIL PROPERTIES WITH EMPHASIS ON COMPARISON OF LABORATORY TESTS AND FIELD MEASUREMENTS

by

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SYNOPSIS

To analyze ground motions during earthquakes, it becomes necessary to obtain strain amplitude-dependent shear moduli and damping coefficients of soils. At two sites, insitu seismic surveys were carried out. Sands sampled from these sites were tested with resonant-column apparatus to obtain shear moduli at small strain. Laboratory test results showed that these two natural sands have smaller shear modulus than uniform clean sands. The comparison of shear moduli from shear wave velocities and those from resonant-column tests was performed and an excellent coincidence was obtained for the both sites.

SHEAR MODULUS G BY RESONANT-COLUMN METHOD

Shear moduli G of sands were obtained with a resonant-column apparatus developed at the Public Works Research Institute(2), (3). This is of Drnevich-type(1) with a hollow cylindrical sample of 25 cm in height, 10 cm in outside diameter and 6 cm in inside diameter. The confining pressure equally applied to the outside and to the hollow of the specimen is supplied by air pressure and the axial load can be applied independently of the confining pressure. With this apparatus shear moduli in the range of shear strain of 10^{-6} to 5×10^{-4} were obtained.

Listed in Table 1 are sands tested in this study. These sands can be divided into two groups: (i) Clean sands which do not include fine particles smaller than 0, 074 mm in diameter and are poor graded. They are made by sieving several natural sands, and (ii) Natural sands, Iruma-sand and Ohgi-shima-sand, which are well graded and include finer particles. Shown in Fig. 1 are gradings of sands tested where TO, OS, ... are the abbreviations of the names of sands listed in Table 1. Shear moduli of air dry clean sands at single shear strain amplitude of 10^{-6}, 10^{-5} and 10^{-4} are shown in Figs. 2 through 4 where p is the mean principal stress denoted by $(\sigma_a + 2\sigma_r)/3$ (σ_a is axial stress and σ_r is radial stress). These figures show that shear moduli G of clean sands tested can be represented approximately by the following empirical equations irrespectively of the kinds of sands.

$$(\gamma = 10^{-6}) \quad G = 900\frac{(2.17 - e)^2}{1 + e} p^{0.38} \tag{1}$$

$$(\gamma = 10^{-5}) \quad G = 850\frac{(2.17 - e)^2}{1 + e} p^{0.44} \tag{2}$$

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$$(\gamma = 10^{-4}) \quad G = 700 \frac{(2.17 - e)^2}{1 + e} \; p^{0.50} \qquad (3)$$

where G is shear modulus in kg/cm^2, p is mean principal stress in kg/cm^2 and e is void ratio. Eq. (3) is identical to the empirical equation for round Ottawa-sand proposed by Hardin,et al(4).

COMPARISON OF LABORATORY TESTS AND FIELD MEASUREMENTS

Insitu borehole seismic surveys were carried out at two sites: Iruma, Minami-Izu-cho and Ohgi-shima, Kawasaki-shi. At the former site, a sandy embankment was damaged by the Off-Izu-peninsula earthquake of 1974. The latter site is a reclaimed land where the borehole accelerometers are installed down to the depth of about 120 m. At Iruma, borehole seismic surveys were carried out at three points. One of the soil properties are shown in Fig. 5. Shear wave velocity measurements were performed at each 2 m depth. Resonant-column tests were performed on sands taken from the deposit just below the ground surface. As the sand deposit is almost uniform to the depth of about 10$\sim$20 m, the sand near the ground surface could represent properties of the whole sand deposit. Tests were carried out on dense air-dry and saturated samples which were completely disturbed. Samples were made by pouring air-dry sand through air into a split mold or by pouring saturated sand into a mold filled with de-aired water. Densification was performed by tamping the split mold with a wooden hammer. Consolidation time was about 1 hr. Considering that the sand deposit is young and plasticity index of the sand is almost zero, the effect of cementation and delayed consolidation could be negligible(5) Therefore shear modulus of the sand deposit could be estimated from the test results on completely disturbed specimens. Illustrated in Fig. 6 are shear moduli at $\gamma = 10^{-6}$, 10^{-5} and 10^{-4} of Iruma sand, which are smaller than those represented by eqs. (1) through (3). It is to be noted that shear moduli of Iruma sand A, C and Z3 which were made by sieving original Iruma Sand are represented by eqs. (1) through (3) as shown in Figs. 2 through 4. This means that shear moduli of sands are affected by grading or content of fine particles. To obtain shear moduli of sand deposits from empirical equations of Iruma sand, it is necessary to estimate effective mean principal stress p' and void ratio e in the ground. First, relative density of every 1 m thick layer was estimated from the relationship of effective overburden pressure σ'_v and N-value proposed by Gibbs and Holtz(6). In the estimation extremely high N-value, provably due to the existence of gravels, were omitted. Secondly, to estimate e, both values of maximum and minimum void ratios were obtained by the method proposed by Yoshimi and Tohno(10). Thirdly, the unit weight of sand γ_t was estimated. Then, effective mean principal stress p' was calculated supposing the earthpressure coefficient at rest to be 0.5. Lastly, shear moduli at $\gamma = 10^{-6}$ and 10^{-4} were obtained by substituting the estimated p' and e into the empirical equations for shear moduli of Iruma sand shown in Fig. 6. Shown in Fig. 7 are the shear moduli from shear wave velocities Vs which is denoted by solid vertical lines and values of shear moduli at $\gamma = 10^{-6}$ and $\gamma = 10^{-4}$ obtained by laboratory tests which are represented by the black circles (G at

$\gamma = 10^{-6}$) and black triangles (G at $\gamma = 10^{-4}$). The solid curve in Fig. 7 indicates shear moduli estimated from these two laboratory-test values of G at $\gamma = 10^{-6}$ and 10^{-4} considering that shear strain amplitudes occurred in the ground during borehole seismic survey decrease with depth on the order of about 10^{-7} to 10^{-5}. It is apparant from this figure that the agreement of the values of shear moduli predicted by laboratory tests with the values by shear wave velocities is satisfactory. Almost same result was obtained for other points at Iruma as shown in Fig. 8. On the other hand, shear moduli obtained from empirical equations for "clean" sands, eqs. (1) through (3), using estimated values of p' and e are also plotted in Figs. 7 and 8 with marks white circles (G at $\gamma = 10^{-6}$) and white triangles (G at $\gamma = 10^{-4}$). Predicted values by eqs. (1) through (3) are much larger than the values from shear wave velocities.

A similar survey was also carried out at Ohgi-shima (Fig. 9). Resonant-column tests were performed for samples taken from just below the ground surface (Fig. 10). Ohgi-shima was reclaimed recently with sands from Sengenyama located in Chiba-prefecture. It is also to be noted that Sengenyama sand A, B and C which have the shear moduli expressed by eqs. (1) through (3) as illustrated in Figs. 2 through 4. From Fig. 11 it is also seen that shear moduli predicted by laboratory tests are almost identical to those obtained by field measurements and that shear moduli estimated by empirical equations of clean sands are overestimated.

CONCLUSIONS

The principal conclusions drawn from this study are as follows.

(1) Shear moduli of each shear strain level of clean sands can be expressed by identical empirical equations irrespectively of sands tested.

(2) Shear moduli of natural sands which are well-graded and contain silty and clayey particles are smaller than those of clean sands.

(3) Shear moduli obtained from laboratory tests is almost identical to those obtained by borehole seismic surveys.

(4) Shear moduli in grounds estimated by laboratory tests vary more naturally with respect to depth when comparing with the variation of shear moduli obtained by seismic surveys.

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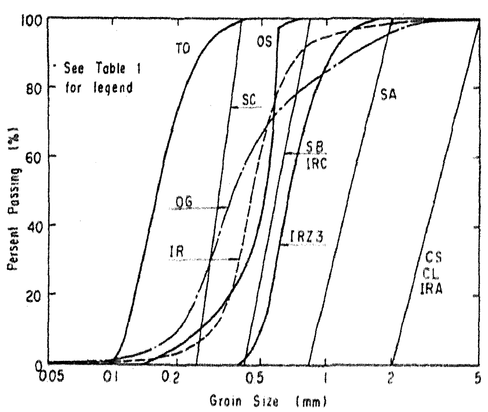

Fig. 1 Gradings of Sands Tested

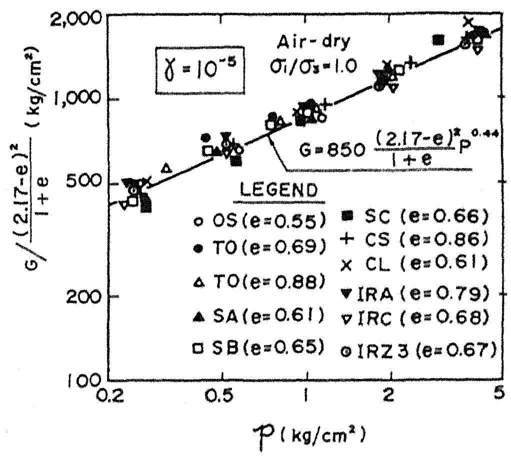

Fig. 3 Shear Moduli at $\gamma = 10^{-5}$ of Clean Sands

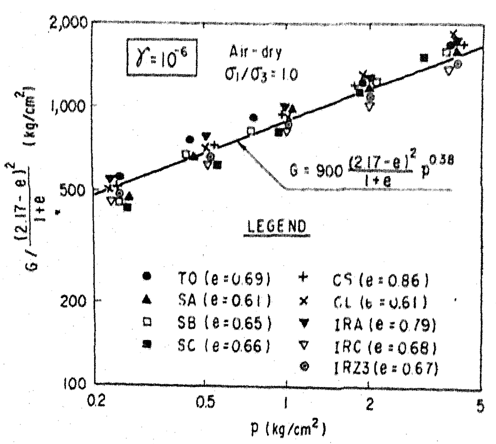

Fig. 2 Shear Moduli at $\gamma = 10^{-6}$ of Clean Sands

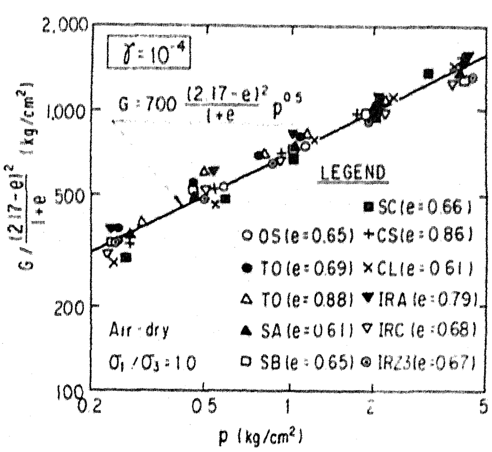

Fig. 4 Shear Moduli at $\gamma = 10^{-4}$ of Clean Sands

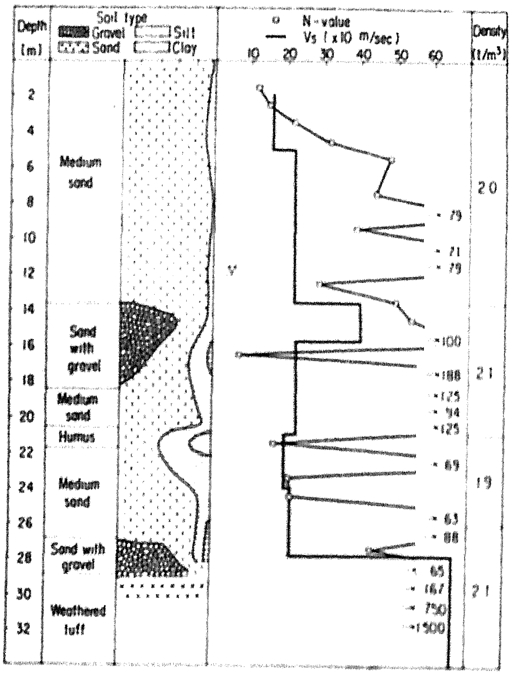

Fig. 5 Soil Profile of Point No. 1 at Iruma

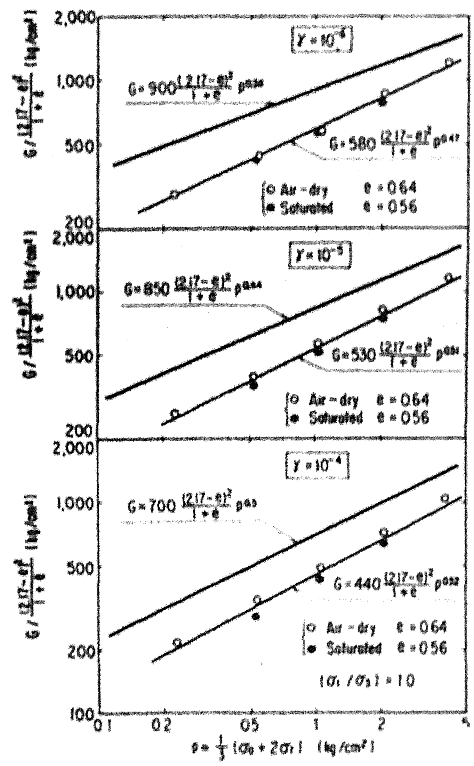

Fig. 6 Shear Moduli of Iruma Sand

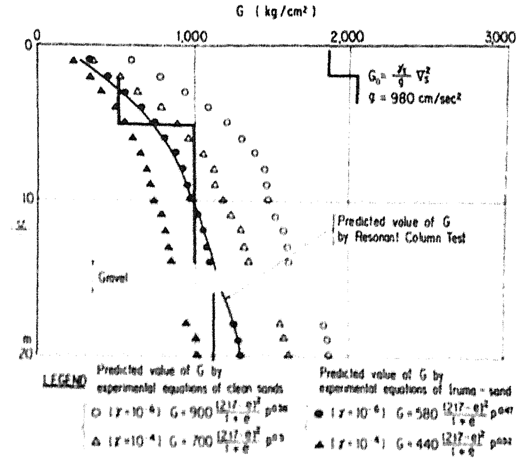

Fig. 7 Comparison of Shear Modulus by Laboratory Tests and Field Measurements at Point No. 1 at Iruma

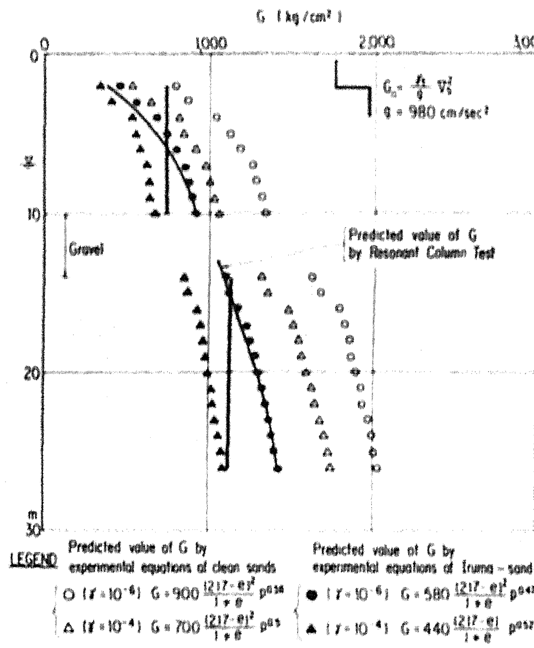

Fig. 8 Comparison of Shear Moduli by Laboratory Tests and Field Measurements at Point No. 3 at Iruma

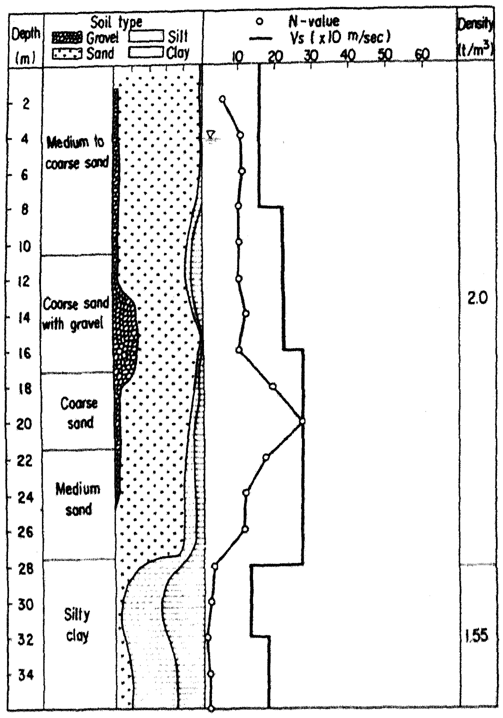

Fig. 9 Soil Profile of Ohgi-shima

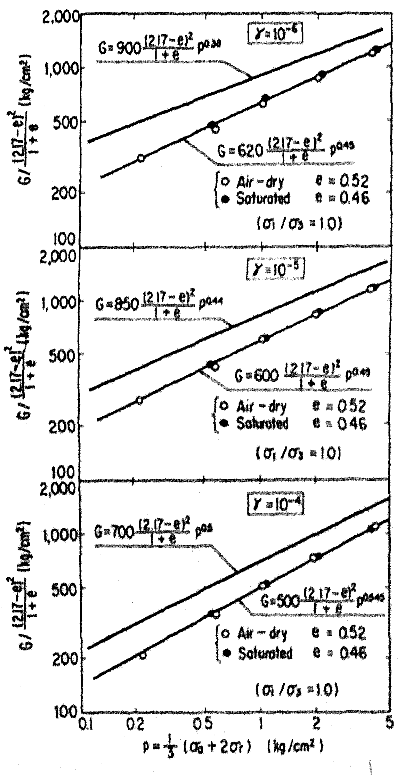

Fig. 10 Shear Moduli at $\gamma = 10^{-6}$, 10^{-5} and 10^{-4} of Ohgi-shima Sand

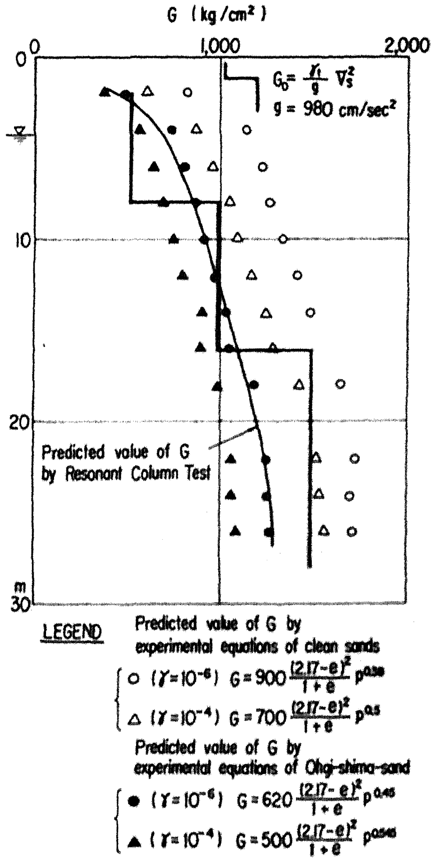

Fig. 11 Comparison of Shear Modulus by Laboratory Tests and Field Measurements at Ohgi-shima

Table 1. List of Materials a)

Material	G_s	D_{10} (mm)	D_{60} (mm)	U_c	$e_{max.}$ b)	$e_{min.}$ b)
Toyoura-sand (TO) c) sub-angular, uniform	2.64	0.12	0.175	1.46	0.96	0.64
Sengenyama-sand A (SA) uniform	2.65	0.85 ~ 2.0 d)		-	0.82	0.61
〃 B (SB) 〃	2.72	0.40 ~ 0.85 d)		-	0.92	0.67
〃 C (SC) 〃	2.68	0.25 ~ 0.40 d)		-	0.98	0.65
Crushed sand-stone (CS) angular, uniform	2.75	2.0 ~ 5.0 d)		-	1.09	0.80
Crushed lime-stone (CL) sub-angular, uniform	2.74	2.0 ~ 5.0 d)		-	0.93	0.64
30-50 Ottawa-sand (OS) round, uniform e)	2.66	0.3	0.54	1.8	0.80	0.48
Ohgi-shima-sand (OG) sub-angular, well-graded	2.69	0.2	0.45	2.25	0.72	0.49
Iruma-sand (IR) angular, well-graded	2.75	0.28	0.56	2.0	0.84	0.57
Iruma-sand A (IRA) angular, uniform	2.67	2.0 ~ 5.0 d)		-	1.06	0.70
Iruma-sand C (IRC) angular, uniform	2.83	0.4 ~ 0.85 d)		-	0.98	0.66
Iruma-sand Z3 (IRZ3) angular, uniform	2.70	0.5	0.74	1.48	0.94	0.68

a) All tests were conducted under $\sigma_1/\sigma_3=1.0$ - condition.
b) $e_{max.}$ and $e_{min.}$ were obtained on air-dry condition.
c) TO, SA, CS, ... are abbreviation for materials tested.
d) Range of diameter.
e) After Drnevich and Richart (1970).[19]

DISCUSSION

N.C. Donovan (U.S.A.)

In the paper by Richart et al (PP 159-164) the suggestion is made that field measured modulus values can be related to laboratory measured values by a constant quantity rather than a constant ratio. The author's experimental results do not appear to agree with their suggestion. Can you comment on this difference ?

Author's Closure

With regard to the question of Mr. Donovan, we wish to state that one of the purposes of our study was to compare laboratory values of shear moduli of sands with in-situ values. For sands, our experimental results agree well with those of Richart et al., comparing Figs. 7, 8 and 9 in our paper with the lefthalf of Fig. 1 in the paper of Richart et al. Another point made in our paper is that the shear moduli of a wide variety of sands at small strain levels are not well represented by a single empirical equation derived from test results on clean sands. Concerning the strain-dependency of clay, no experimental results are presented in our paper.